DIGITAL TWINS FOR ADVANCED MANUFACTURING: THE STANDARDIZED APPROACH

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ABSTRACT

Digital Twins are becoming more prevalent in a wide range of industries such as manufacturing, construction, smart city, and healthcare for various purposes, including observing, predicting, optimizing, and controlling. Digital Twins are in the early adoption stage. Currently, few standards directly address Digital Twins and a commercial ecosystem of Digital Twins has not been well established. Developing and implementing Digital Twins present significant challenges. Most current Digital Twin applications are customized solutions, which are expensive to create and difficult to integrate with other systems. Foundational work is needed to support an open marketplace for Digital Twin developers, users, and technology service providers. This includes the development of standardized frameworks, reference models, and interfaces to provide a solid foundation for ensuring interoperability, reliability, validity, security, and trust. This Chapter identifies implementation challenges for Digital Twins for manufacturing, reviews relevant standardization efforts, introduces the ISO Digital Twin framework standard for manufacturing, presents use cases, and discusses potential research topics and future standardization directions.

Keywords: Digital Twin, Standards, Advanced Manufacturing, Robot Workcell.

1 INTRODUCTION

The idea of developing physical mockups of planned objects, infrastructure, or scenes has been practiced by humans for millennia. NASA provides one of the notable applications of twinning from the 1960s during the planning and execution of space missions. Mission planners created two similar space vehicles. One was sent on a mission while its physical "twin" remained on Earth. The vehicle on Earth emulated the state of the flying twin and could be used to test possible solutions to problems encountered with the flying twin [1]. As computer technology advanced, physical models gave way to digital models. The Digital Twin concept gained more momentum in 2002 after Dr. Grieves presented his vision of real space, virtual space, and information flowing between real and virtual spaces [2]. The key idea is the state synchronization of the real space and virtual space. However, not until recently did this concept become one of the top strategic technology trends. The advancement of technologies such as the Internet of Things (IoT), smart sensors, Artificial Intelligence (AI), and cloud computing facilitate the realization of Digital Twins.

Digital Twins involve highly complex functional subsystems, including data collection, processing, communication, modeling, analytics, visualization, simulation, optimization, and control. Some of these could be distributed systems. This complex system of systems presents significant challenges for manufacturers to understand and seamlessly integrate these diverse functional subsystems. Many companies already have some form of digital transformation efforts underway. Others may already have multiple versions of digital solutions from various vendors. Some vendors claim that they have complete solutions for Digital Twin development. However, it is impossible to have all companies discard existing digital systems and source new replacements from the same vendor because not all manufacturers are technically able nor can afford to redesign and replace their entire plants. Therefore, existing systems and technologies must be integrated when implementing new Digital Twins. Interoperability standards are needed to support the communication and integration between (1) the physical and virtual systems, (2) multiple Digital Twins, and (3) Digital Twins and legacy systems such as Manufacturing Execution Systems (MES), Enterprise Resource Planning (ERP), and Product Life Cycle Management (PLM).

A Digital Twin comprises three main components - the physical system, the virtual representation of the physical system, and bi-directional communication between the physical and virtual worlds. Recent studies have introduced two more dimensions: data and service [3]. It has then been noted that a framework is needed to realize a Digital Twin, which comprises different components so developers can use it for various applications and domains. While each Digital Twin may differ in composition details, a high to medium-level general framework can help reduce the Digital Twin development effort. Researchers have developed frameworks for various aspects of Digital Twin development. Frameworks that emphasize the two-way communication between the physical twin and the Digital Twin have been proposed [4, 5]. Many Digital Twins today are implemented for real-time state monitoring. The airline industry has used Digital Twins to monitor jet engines for many years. These types of digital twins use one-way synchronization. They receive data from the physical object but do not provide control feedback.

Galli et al. [6] analyzed a variety of proposed frameworks for building Digital Twins. This research focused on the structure of the frameworks to find correlations in terms of form and conceptualization. The results showed three types of architectures used for the Digital Twin. The first is the traditional and is based on the original framework proposed by Grieves and Vickers [7]. This architecture supports the Digital Twin in paralleling the real system, discussing interfaces and interoperability with operations management systems. It also ensures synchronization between the physical system and its corresponding twin. The second is the "service-oriented" type, which consists of four components: a physical shop floor, a virtual model of the shop floor, a service system, and the shop floor Digital Twin data. The third architecture is the fractal, where local or specialized Digital Twins make up the global Digital Twin, each with a similar structure. Khan et al. proposed a six-dimensional framework to include (1) a physical asset, (2) a digital duplicate of the physical asset, (3) data generated by the physical asset, (4) programs that improve product performance and make the production process more efficient, (5) spiral-rings like iterations that generate a more optimized product or efficient production process, (6) synchronization between the physical and the digital [4].

Despite these efforts, the Digital Twin technology is still in its early stages. No universal definition, implementation framework, and protocol are available. There is also a lack of comprehensive and in-depth analysis of Digital Twins from the perspective of concepts, technologies, and industrial applications research [8]. Further, the ecosystem of Digital Twins is not well established, and most Digital Twins are developed using customized solutions. Customized solutions do not support reuse and are costly and time-consuming. A systematic approach is needed to characterize and manage Digital Twin subsystems to ensure cross-disciplinary interoperability and credibility of the Digital Twin. Standards are the solutions to enable such interoperability. However, few standards have been developed for Digital Twins so far.

According to Accenture research, companies are not taking full advantage of Digital Twins because most Digital Twin applications are standalone for single functions, which focus on functional optimization instead of enterprise optimization, and have no comprehensive strategy for data integration and sharing [9]. Additionally, if a Digital Twin is the current representation of a physical asset, the associated Digital Twin data at any life cycle stage could be helpful for future asset management. The architecture or mechanism for the flow of information about a product's performance and use from design, production, use, disposal, and recycling is referred to as the digital thread [10]. Using the digital thread will enable the traceability of Digital Twins from requirements to the retirement of the physical asset. Interoperability among Digital Twins for different life cycle stages through digital threads should help overcome these challenges. Standardized data representation will help avoid customized Digital Twin development approaches and the duplication of efforts. Digital threads can also provide an integrated view of the physical asset for Digital Twin development, avoiding redundancy during information exchange.

To make the best use of Digital Twins, manufacturers need to apply interoperability standards from both systems of systems and life cycle perspectives. In addition, standards on vocabulary, reference architecture, and trustworthiness can help ensure the interoperability, value, and credibility of the Digital Twins. These standards will enable manufacturers to build, manage, and deploy their Digital Twins more efficiently.

This Chapter focuses on a standardized approach to building Digital Twins for advanced manufacturing. It identifies current challenges for manufacturers to implement their Digital Twins, reviews relevant standards efforts, introduces the new ISO Digital Twin standard, presents use case scenarios, and discusses some potential standards development research directions. The rest of the chapter is organized as follows: Section 2 discusses various applications of Digital Twins, Section 3 presents how standards help address the challenges of implementing and adopting Digital Twins that manufacturers face, Section 4 introduces ISO standard, ISO 23247 - Digital Twin Framework for Manufacturing, Section 5 discusses additional relevant standards, Section 6 describes a case study of how standards can be applied to building a Digital Twin of a robot work cell, Section 7 discusses potential topics and research directions towards standardization, and Section 8 summarizes the chapter and presents future work.

2 APPLICATIONS AND ENABLING TECHNOLOGIES FOR DIGITAL TWINS

Digital Twins are becoming increasingly prevalent in a wide variety of industries, including manufacturing, construction, smart cities, and healthcare. The applications of Digital Twins include system monitoring, anomaly detection, prediction, optimization, and control. The major general classifications of Digital Twins, shown in Figure 1, are descriptive, diagnostic, predictive, prescriptive, and intelligent Digital Twins. From left to right, Figure 1 shows the different Digital Twin functionalities, with increasing complexity from monitoring to intelligent control, to support appropriate decision-making and automation. The bulletized items in each box are examples of enabling technologies for that category of Digital Twins. Each category is described in the following [11].

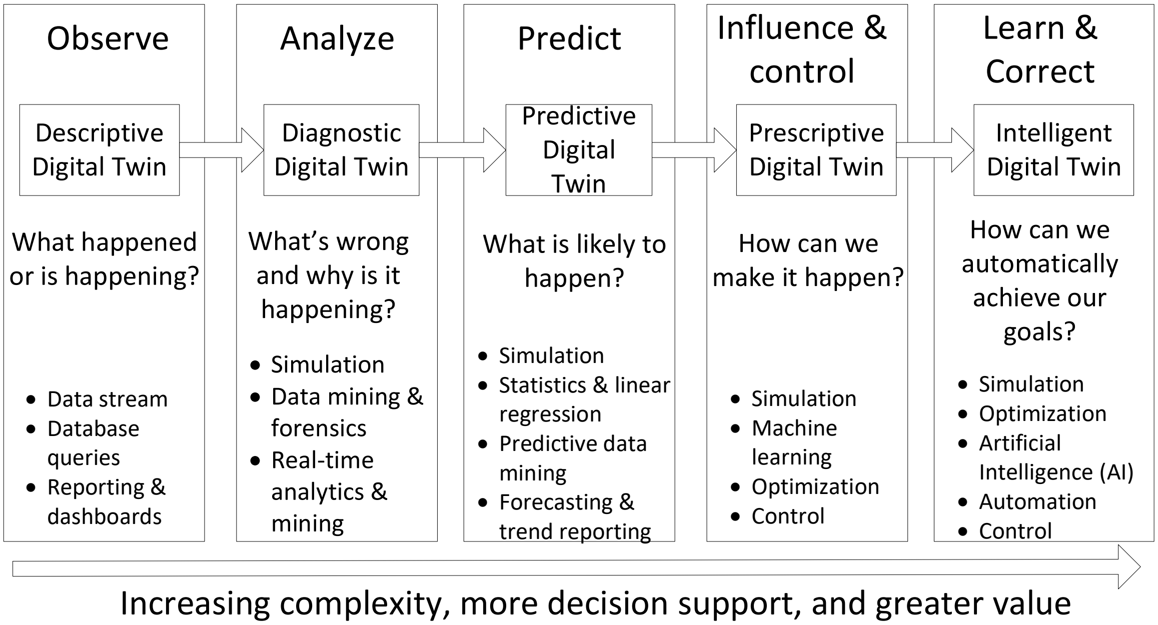

Figure 1: Various applications of Digital Twins with examples of supporting technologies.

- *Descriptive Digital Twins* observe their physical counterparts to identify what has happened or is happening. These kinds of Digital Twins can generate different views of the data collected using smart sensors based on the purpose of the Digital Twin. Based on stakeholders' requirements, data and parameters can be visualized in the form of text, tables, and charts. For example, one of these important data is the cycle time of each product type during production. Enabling technologies may include real-time data streaming, database queries, and dashboard reporting.
- *Diagnostic Digital Twins* analyze what has gone wrong and why it has happened or is happening to their physical counterparts. Diagnosis includes analyses of the impact of a data input and an operational strategy on key performance indicators (KPIs). For example, a product's cycle time increase may be caused by machine breakdowns or bad scheduling decisions. Diagnostics are supported by technologies and methodologies such as simulation, data mining, machine learning, and analytics.
- *Predictive Digital Twins* predict what will happen and when it will happen. These kinds of Digital Twins can be used to estimate when a machine tool or robot deterioration will likely reach a point of failure based on past performance patterns. They can also pinpoint the cause or source of failure. Enabling technologies may include modeling and simulation, predictive data mining, and parameter tracking. Digital Twins integrated with machine learning can be used to predict cycle times for incoming manufacturing orders [5].
- *Prescriptive Digital Twins* provide the influence and control of the physical counterparts and decide how to make it happen based on the objectives of the Digital Twins. These kinds of Digital Twins can help identify the strategies and inputs leading to optimal performance. For example, prescriptive analytics provide the best possible input parameters and methods that enable cycle-time reduction and increase throughput. Enabling technologies may include simulation, optimization, and control.
- *Intelligent Digital Twins* are envisaged to control their physical counterparts based on the strategies and parameters identified by the prescriptive Digital Twins. These kinds of Digital Twins can learn new strategies based on the data collected and take actions accordingly, which could include dynamically adjusting themselves based on the changes in their physical counterparts to keep up with them or based on the Digital Twin objectives to ensure the physical counterparts operate optimally. Artificial Intelligence (AI), including large language models, is the primary modeling technique used for modeling the

intelligent Digital Twin. Other enabling technologies may include simulation, optimization, automation, and control.

The kind of Digital Twin to be implemented depends on the use case and is driven by the objective and scope of the Digital Twin.

3 HOW STANDARDS SUPPORT DIGITAL TWIN DEVELOPMENT AND INTEGRATION

As discussed in Section 1, there are still significant challenges for manufacturers, especially Small and Medium-sized Enterprises (SMEs), to implement their Digital Twin applications efficiently and effectively. Current implementations mostly use ad hoc, customized approaches. Customized solutions not only increase the development time and cost but also make it challenging to integrate with other systems and do not support reuse. Standards are needed for manufacturers to go beyond custom, expensive Digital Twins to an affordable marketplace of products and tools for Digital Twins. Standards, such as frameworks, reference models, and interfaces, will provide a solid foundation for Digital Twin developers, users, and technology and service providers to ensure interoperability, reliability, validity, security, and trust.

Standards for Digital Twins will facilitate the composition and integration of Digital Twins by providing guidelines, methodologies, common terminologies, architectures, and interface specifications. These standards can help make the creation, integration, update, and validation of Digital Twins more accurate and consistent. Standards can also help formalize requirements for Digital Twin projects, enable the use of building blocks for Digital Twin implementations, analyze Digital Twin performance, communicate between suppliers, partners, and customers, secure Digital Twin information and protect privacy, and facilitate the verification and validation of Digital Twins according to stakeholders' requirements. Ultimately, standards will help achieve "plug and play," i.e., enabling interoperability between Digital Twins and supporting software and hardware from various vendors. In different areas, standards support the following:

- Defining a common language for data representation, communication protocols, and Application Programming Interfaces (APIs) to ensure Digital Twin systems can understand and interact with each other's data. Examples of APIs include those for data query, data update, and data synchronization.
- Developing shared metadata and ontologies to describe the properties, attributes, and relationships within Digital Twins for easy mapping and translating data between Digital Twins.
- Developing tools or middleware that can map data from one Digital Twin's format to another using techniques such as data transformation, data normalization, or data translation.
- Implementing robust security measures to ensure only authorized Digital Twins can access and interact with each other using techniques such as authentication, encryption, and access control.

4 DIGITAL TWIN FRAMEWORK FOR MANUFACTURING

The ISO standard, ISO 23247 - Digital Twin Framework for Manufacturing, was created to facilitate the implementation of Digital Twins in manufacturing. The standard defines a "Digital Twin in Manufacturing" as a "fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation [12]." It provides a generic guideline, a reference architecture, and a framework for Digital Twin applications in manufacturing. The standard also provides examples of data collection, data communication, integration, modeling, and applications of relevant standards [12]. The standard provides procedures for manufacturers and solution providers to analyze Digital Twin requirements, define scope and objectives, use common terminologies, comply with a generic reference architecture, and integrate multiple existing standards for various purposes. The framework includes the sub-entities and components as building blocks for manufacturers to pick and choose for their own case-specific Digital Twin development. It helps manufacturers systematically identify and determine subsystems and components, their relationships, and the characteristics of their interactions from which appropriate standards can be selected for interoperability.

A key feature of ISO 23247 is that it enables the deployment of the digital thread, implying that model-based engineering standards for various stages of a product life cycle can be included in the framework. For example, for the Digital Twins developed to support a product at different stages, including design, manufacturing, and inspection, relevant standards such as Standard for the Exchange of Product Model Data (STEP) [13], MTConnect [14], and Quality Information Framework (QIF) [15] can be applied. Therefore, the standard supports Digital Twins' compatibility and interoperability throughout the life cycle stages, allowing information reuse and traceability.

The standard series includes four parts: (1) overview and general principles, (2) reference architecture, (3) digital representation, and (4) information exchange. The reference architecture in the standard includes a reference model with domains and entities. There are four domains (layers), each with a logical set of tasks and functions performed by functional entities. Figure 2 shows the entity-based reference model and an illustration of the four domains and their interactions [16]. Each domain is briefed as follows.

- The observable manufacturing domain: contains the Observable Manufacturing Elements (OMEs), including any physical artifact, process, or behavior such as personnel, equipment, material, processes, facilities, assets, and systems on the factory floor. These OMEs are represented by the Digital Twins.
- The device communication domain: is a layer between OMEs and their Digital Twins to support data exchange and synchronization. OMEs are monitored, and real-time data are collected using device sensors and standard protocols in the OME domain. This domain is also responsible for transferring commands and signals for control and actuation of the OMEs.
- The Digital Twin domain, or core domain: is responsible for the modeling, operating, and managing Digital Twins. This domain hosts models, applications, and services such as data analytics, simulation, and optimization to support provisioning, monitoring, analysis, and synchronization. It also interacts with users and systems, including other Digital Twins. As indicated in the definition, Digital Twins are built "fit-for-purpose" because each has its own objectives, is context-dependent, and only requires relevant data and models. The purpose dictates the information content, model fidelity, and frequency of synchronization.
- The user domain: includes users or systems such as a human, a device, an application, or a system that uses applications and services provided by the Digital Twin domain.

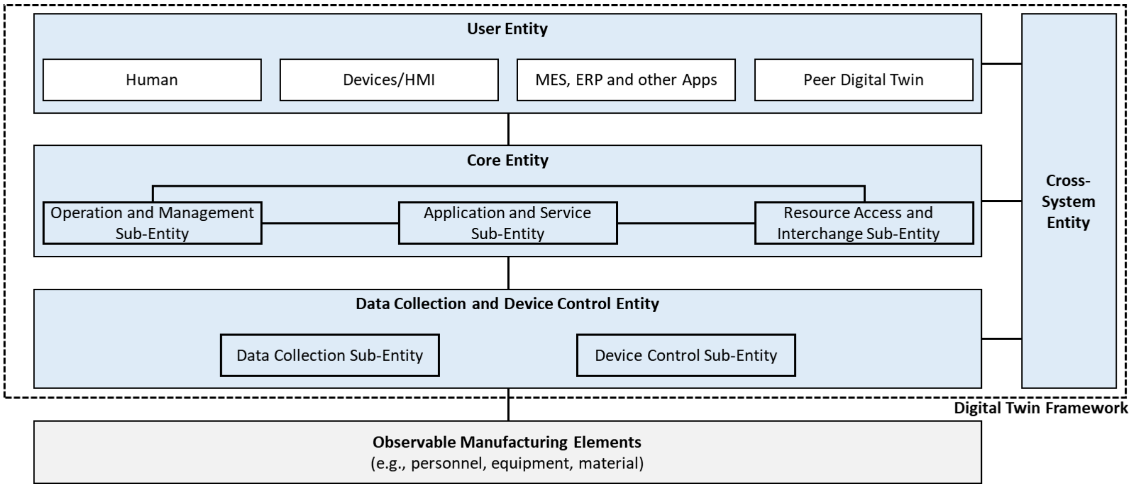

Figure 2: Functional view of the Digital Twin reference model for manufacturing.

The cross-system entity in Figure 2 is an entity that resides across domains to provide common functionalities such as data translation, data assurance, and security support. Digital Twins can be developed based on the Digital Twin Framework depicted within the dotted line in Figure 2. The framework supports the applications of IoT infrastructure for data collection, communication protocols for data transmission, and information flows between entities of different domains - OMEs, Data Collection and Device Control, Digital Twin Core, and User layers.

Developers tested the Standard by implementing several industry use cases to demonstrate and validate the Standard. The use cases included a Digital Twin for robot drill and fill to increase equipment utilization, a Digital Twin that optimizes the sizes of aircraft fasteners, and a Digital Twin to optimize Computer Numerical Control (CNC) cutting tool life. These use-case implementations provided valuable feedback to standards developers and demonstrated the viability of the standard framework for constructing digital twins [17].

5 ADDITIONAL RELEVANT STANDARDS

Digital Twin standards, such as architectural frameworks, can provide implementation guidelines for developing Digital Twins. Other existing standards can support specific Digital Twin functionalities such as data collection, data communication, information modeling, systems integration, simulation modeling, and automation and control. This section identifies some examples of manufacturing standards that could apply to various aspects of the Digital Twin development. Standards related to information security, data assurance, and trustworthiness are also necessary, but not listed in this Section.

5.1 Frameworks and Architectures

- IEC 62832-1: 2020, Digital Factory Framework defines a framework to establish and maintain the digital representations of production systems throughout their life cycle. This framework supports a consistent exchange of information between all processes and partners. Information becomes understandable, reusable, and exchangeable throughout the production system life cycle [18].
- IEEE P2806:2019, System Architecture of Digital Representation for Physical Objects in Factory Environments, supports the development of digital factories. It describes the objective, components, data sources required, and procedure of digital representation in factory environments [19].
- IEC 63278-1: Asset Administration Shell for industrial applications - Part 1: Asset Administration Shell (AAS) structure (Under development within IEC TC65 WG24) [20]. AAS aims to enable one or more software applications to exchange information and use that information in a trusted and secure way. It specifies the connector between the real and virtual worlds and includes a model of the shell covering the fundamental concepts: Asset, Submodel, and Concept Description. Identifiers are defined for all elements in the model, concept descriptions, and property definitions of external repositories such as ECLASS and IEC CDD. Mappings of the AAS model are specified for several widely used information models such as XML, JSON, RDF, OPC UA, and AutomationML.
- ISO/IEC 30141:2018, Internet of Things (IoT) - Reference Architecture provides a common vocabulary, reusable designs, and industry best practices. It starts with collecting the essential characteristics of IoT, abstracting them into a generic IoT conceptual model, and deriving a high-level systematic reference with subsequent dissection of that model into five architectural views [21].
- ISO/IEC 21823-1:2019, Internet of things (IoT) - Interoperability for IoT systems - Part 1: Framework provides an overview of the interoperability of IoT systems and the various entities within them. It enables IoT systems to be built so the entities of the IoT system can exchange information efficiently. It also supports peer-to-peer interoperability between IoT systems [22].
- ISO/IEC/IEEE 15288:2015, Systems and software engineering - System life cycle processes establish a common framework of process descriptions for describing the life cycle of systems. It

defines a set of processes and associated terminology that can be applied at any level in a system's structure. They can manage the stages of a system's life cycle. It also provides processes that support the definition, control, and improvement of the system life cycle processes [23].

- Microsoft Digital Twin Definition Language (DTDL) - A language for describing models and interfaces for IoT Digital Twins. DTDL is based on JSON-LD and is programming language independent. DTDL is used in different Microsoft services such as IoT Hub, IoT Central, and Azure Digital Twins; it is also used to represent device data in other IoT services such as IoT Plug and Play. DTDL covers the resource description and not resource discovery and access. Resources (interfaces) contain telemetry, properties, commands, relationships, and components [24].
- The High-Level Architecture (HLA) defines an architecture for distributed simulation, its components, and the rules that outline the responsibilities of HLA federates and federations for a consistent implementation. The standard also supports maintaining the information model of each simulation to retain its meaning and purpose but enables data communication and time synchronization of the distributed simulation systems [25].

5.2 Data Collection, Data Modeling, and Data Exchange

- MTConnect supports interoperability by providing a vocabulary for manufacturing equipment, making structured contextualized data possible, and avoiding proprietary formats. Data sources of MTConnect include equipment, sensor packages, and other factory-floor hardware [14].
- OPC-UA (Unified Architecture) is a platform-independent standard used to send messages between clients and servers over diverse networks with syntactic interoperability [26].
- The MTConnect-OPC UA Companion Specification supports interoperability and consistency between MTConnect specifications and the OPC-UA specifications, as well as devices and software that implement those standards [27].
- ISO/IEC 20922, Information Technology - Message Queuing Telemetry Transport (MQTT) v3.1.1, is a data protocol that supports client and server messaging transport for publishing and subscribing. It is open and simple in design and suitable for use in machine-to-machine (M2M) communication and IoT contexts [28].
- ISO/IEC 17826, Information Technology - Cloud Data Management Interface (CDMI), specifies how to access and manage stored cloud data [29].
- ISO 13374 series, Condition Monitoring and Diagnostics of Machines - Data Processing, Communication, and Presentation, provides basic requirements for open software specification [30].
- ISO/IEC 30161:2020, Internet of Things (IoT) - Requirements of IoT data exchange platform for various IoT services, specifies requirements for an IoT data exchange platform for : (1) middleware components of communication networks allowing the co-existence of IoT services with legacy services, (2) end-points performance across the communication networks among IoT and legacy services, (3) IoT-specific functions allowing the efficient deployment of IoT services, (4) IoT service communication networks' framework and infrastructure and (5) IoT service implementation guideline for IoT data exchange platforms [31].
- AutomationML (Automation Markup Language) is a neutral data format based on XML that can store and exchange information for plant engineering, connecting heterogeneous modern engineering tools. Disciplines include mechanical plant engineering, electrical design, human-machine interface development, Programmable Logic Controller (PLC), and robot control [32].
- The Core Manufacturing Simulation Data (CMSD) standard provides an information model schema to support data representation and exchange between simulation and other manufacturing applications [33].
- ISO 15531, Industrial Automation Systems and Integration - Industrial Manufacturing Management Data supports information exchange between software applications in production activities, including planning, scheduling, simulation, control, and execution [34].

- ISO 14649 -201; Industrial Automation Systems and Integration – Physical Device Control – Data Model for Computer Numerical Control Controllers - Part 201: Machine Tool Data for Cutting Processes describes technology specific to machine tools. It defines data elements for manufacturing and machine characteristics [35].
- ISO/IEC 21823-2:2020, Internet of things (IoT) - Interoperability for IoT systems - Part 2: Transport interoperability, specifies a framework and requirements for transport interoperability to enable the construction of IoT systems with information exchange, peer-to-peer connectivity, and seamless communication between different IoT systems and among entities within an IoT system [36].
- ISO/IEC 21823-3:2021, Internet of Things (IoT) - Interoperability for IoT systems - Part 3: Semantic interoperability, provides: (1) basic concepts for IoT systems including requirements of the core ontologies for semantic interoperability, (2) best practices and guidance on how to use ontologies to develop domain-specific applications, (3) relevant IoT ontologies along with comparative study of the characteristics and approaches in terms of modularity, extensibility, reusability, scalability, interoperability with upper ontologies and (4) use cases and service scenarios that exhibit necessities and requirements of semantic interoperability [37].
- ISO/IEC 21823-4:2022, Internet of things (IoT) - Interoperability for IoT systems - Part 4: Syntactic interoperability, describes five facets of IoT interoperability: transport, semantic, syntactic, behavioral, and policy. It includes specifications on how to achieve syntactic interoperability among IoT devices and a framework for processes for developing information exchange rules related to IoT devices [38].

5.3 Digital Representation

- The American Society of Mechanical Engineers (ASME) Y14.26M, Digital Representation for Communication of Product Definition Data, focuses on the representation and communication of data to define products. It supports product data exchange developed in computer-aided manufacturing (CAM) systems [39].
- ISO 10303, Automation Systems and Integration - Product Data Representation and Exchange, also known as Standard for the Exchange of Product model data (STEP), supports the exchange of product manufacturing information [13].
- ISO 10303-IR 105, Automation Systems and Integration - Product Data Representation and Exchange - Part 105: Integrated Application Resource: Kinematics focuses on the representation of kinematics information of a mechanical product [40].
- Quality Information Framework (QIF) - This framework standard enables the capture, use, and re-use of metrology-related information throughout the Product Life Cycle Management (PLM) and Product Data Management (PDM) domains. It supports the creation of digital threads. It applies to product design, manufacturing, and quality inspection. It relies on the Extensible Markup Language (XML) standard and contains a library of XML schemas. It supports data integrity and interoperability in implementing model-based enterprise and IoT [15].
- ASME B5.59-2, Information Technology for Machine Tools Part 2, defines the properties needed to describe machine tools used for milling and turning [41].
- ISO 13399, Cutting Tool Data Representation and Exchange, provides a model and a reference dictionary to represent cutting tools. EXPRESS schema is used for the product description, and product files can be generated according to the schema [42].
- ISO 16400, Equipment Behaviors Catalogue (EBC) defines a template and rules for describing equipment behaviors, such as state transition and time series of operation results, that are produced because of machine activities to be registered in the common repository. It specifies the methodology to construct catalogs of equipment behavior to plan and analyze production system performance [43].

- Predictive Model Markup Language (PMML) is used to develop predictive and descriptive models and to represent pre- and post-processed data. PMML is based on XML and supports the representation of statistical and data-mining models and the model sharing between PMML-compliant applications. Examples of models include neural networks, decision trees, Gaussian progress, and Bayesian networks [44].

With these relevant standards from various functional categories, users can select those applicable to their Digital Twin implementations.

6 A USE CASE OF DEVELOPING DIGITAL TWINS WITH A STANDARDIZED APPROACH

In this section, a robotic work cell, Digital Twin, is discussed to exemplify the application of relevant standards. The work cell consists of collaborative robot arms for material handling and machine tending, a CNC machine tool for machining, and a Coordinate Measuring Machine (CMM) for product geometry measurements and quality control. Figure 3 shows the workflow and equipment for the use case scenario in the work cell. The workflow includes receiving parts, loading parts to the CNC (by ROBOT #1), cutting the parts, unloading parts from the CNC (by ROBOT #1), loading parts to the CMM (by ROBOT #2), inspecting the parts, and offloading parts from the CMM (by ROBOT #2). Parts that fail the inspection will be sent to the rework buffer by ROBOT#2. The cell has a single input location and a single output location. The robots are fitted with a 2F-85 gripper to handle components with different geometries effectively.

One of the research objectives is to build a process digital twin that is a composite of the Digital Twins of each individual component.

The standards used in implementing the use case include ISO 23247, MTConnect, STEP, QIF, and ASME Verification, Validation, and Uncertainty Quantification (VVUQ).

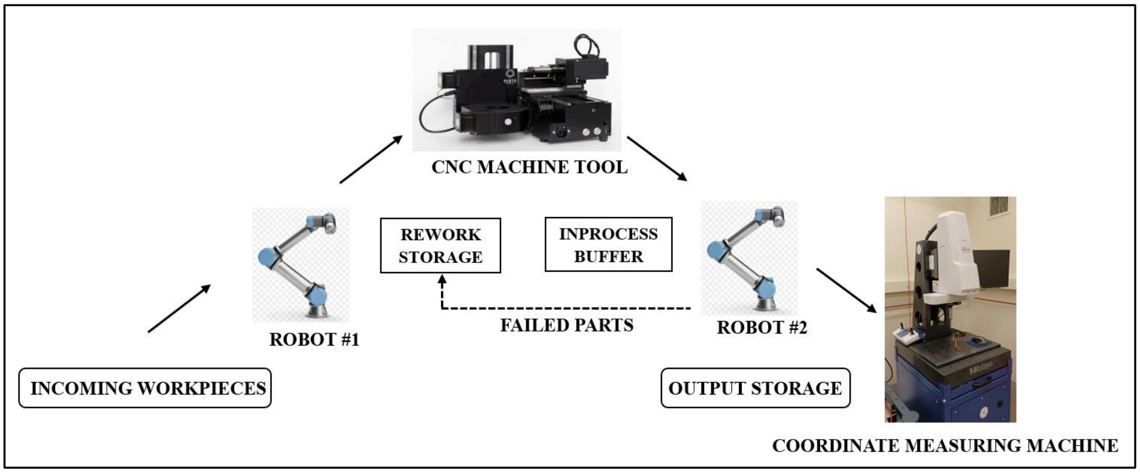

Figure 3: Workflow through machines and equipment in the robot work cell.

6.1 ISO 23247

Based on the Digital Twin framework introduced in Section 3, each piece of equipment in the work cell is treated as an OME, for which data need to be collected, and Digital Twins for various scenarios must be developed. In this section, we focus on one robot arm in the work cell to showcase the method of Digital Twin development.

The ISO Digital Twin framework standard is instantiated for the robot arm (UR5e), whose operations include picking and loading a workpiece to a CNC machine tool. Figure 4 illustrates the instantiation of the framework for the robot arm. The figure shows data being collected from the robot arm through a MTConnect adapter. The Digital Twin entity comprises the simulation model of the robot arm and analytical models that manipulate real-time data to support decision-making. The modeling method and environment support the three-dimensional geometry of the robot arm components, including the robot base, links, joints, end effector, and workpiece. The user entity includes the developer and user of the Digital Twin, production software systems, or other Digital Twins. Similarly, the standard can be instantiated for the cutting part, the CNC machine, and the CMM.

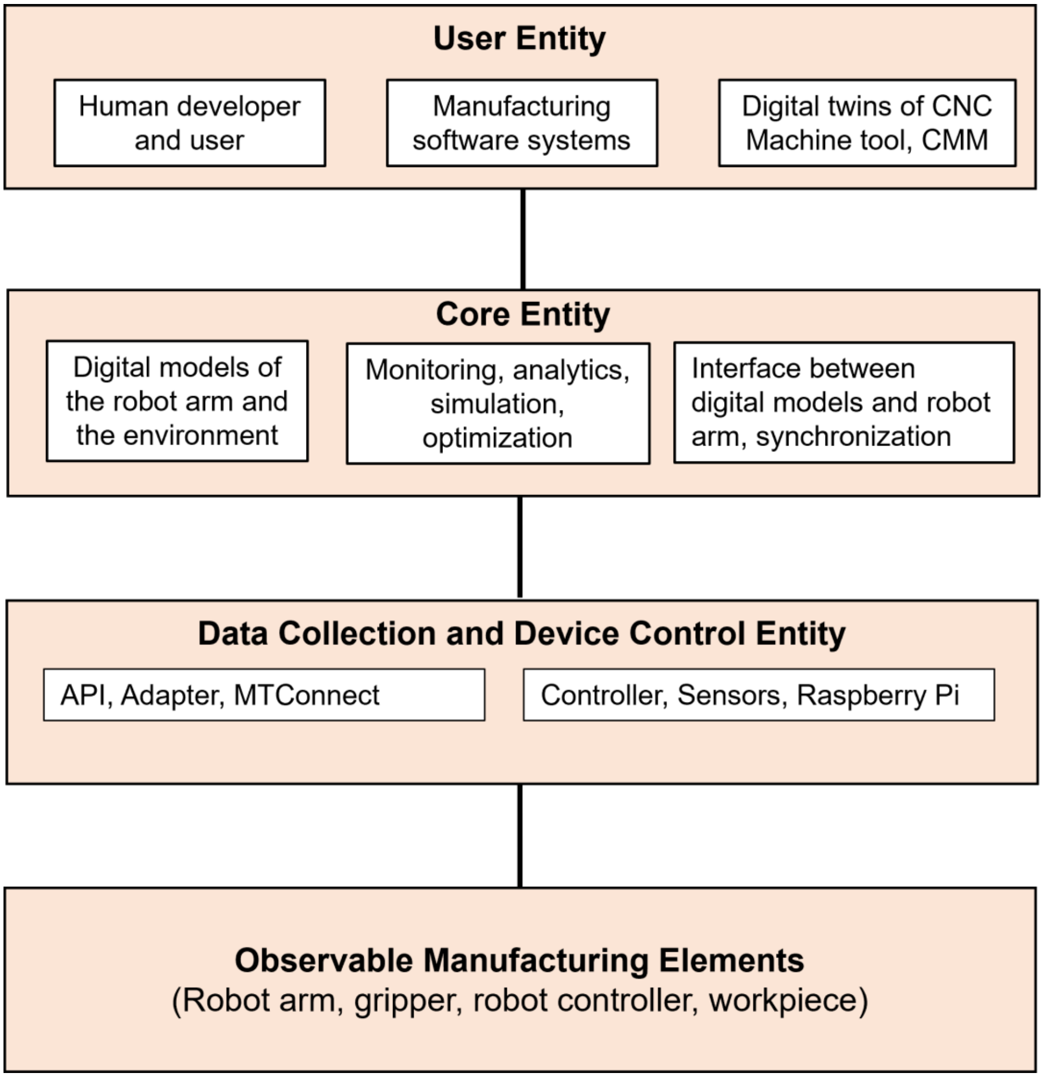

Figure 4: Implementation method of building a Digital Twin for the robot based on ISO 23247.

6.2 MTConnect

The process of acquiring data and building a scalable data pipeline for the work cell has multiple components: (1) collecting real-time operational data from the robot, (2) leveraging the MTConnect standard to provide defined machine data and make it available in a standard format, and (3) developing a set of tools to enable client-side use of the MTConnect agent.

Operational data collection: To collect the operational data from the UR5e robot arm, we utilized the Universal Robot's Real-Time Data Exchange (UR-RTDE) interface with APIs supporting data collection. Several data items collected include angular position, velocity, acceleration, torque, current, and temperature for each of the six joints of the robot arm. Universal Robots also shows the data items (and the corresponding units) that the vendor offers through the UR-RTDE interface.

MTConnect interface: Implementing the MTConnect standard requires an adapter and an agent. The adapter serves as a data collection element from the equipment while the agent collects data from the adapter. Many machine vendors provide a preinstalled adapter but not the UR5e robot. The adapter was installed on an interface connected to the robot arm. The adapter packages data into a format that is readable by the agent. The agent provides an application interface to retrieve the MTConnect data gathered from the adapter. Figure 5 shows the data flow from a physical device (UR5e) to the Digital Twin. A semantic structure was provided for the physical data generated by the UR5e robot arm through MTConnect. This semantic structure includes data tags and units based on the MTConnect 2.0 Standard [42]. Using the Python UR-RTDE API, a socket-based adapter that sends MTConnect-compliant data to the agent was developed. An instance of the MTConnect agent receives and serves the data in a machine-readable format.

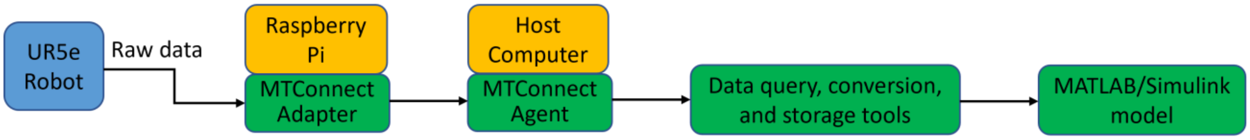

Figure 5: Data pipeline for the UR5e robot Digital Twin.

Client-Side integration: The MTConnect agent is implemented in C++ and displays data in XML format on a Hypertext Transfer Protocol (HTTP) server. The tool used for modeling the robot work cell is the Simulink/Simscape, which can input comma-separated values (CSV) where multiple data items over a time interval are recorded and synced up to their respective timestamps (UTC format). The tools have been developed to parse the XML output from the MTConnect Agent, populate a 2-dimensional array, and store the array in a CSV file.

6.3 STEP

To develop a physical model of the robot arm, Computer Aided Design (CAD) models of its components and those of the work environment are fundamental. These models include the description of the geometry of the links and how they are connected to the robot arm. These CAD models are imported into the Digital Twin environment to create a physical model of the UR5e robot arm. The CAD models for the gripper are "assembled" into the end effector in the AutoCAD Inventor environment, exported to the Digital Twin environment, and "attached" to the robot arm model. Figure 6 shows the physical and virtual models of the robot arm with the attached end effector.

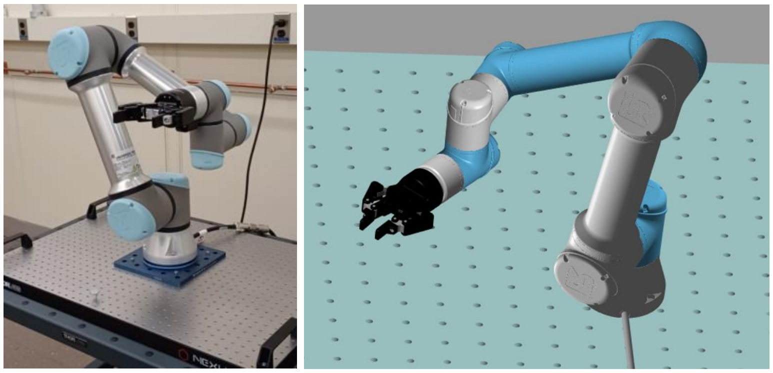

Figure 6: The physical and virtual model of the UR5e robot arm with attached gripper.

The CAD models of the part, CNC, and CMM can be in STEP standard format, which allows easy exchange and visualization. The design part model in STEP will also be used to compare the measurements of the finished product.

6.4 Quality Information Framework (QIF)

QIF provides an integrated model for manufacturing quality information. The CMM provides measurement information about a product regarding conformance to specifications per Geometric Dimensioning and Tolerancing (GD&T) design. Design tolerances are defined by the amount a feature is allowed to vary from the nominal. Assigning GD&T to a designed part is a way to consider process variation within manufacturing. This product data is obtained directly from the design process and should be available throughout the product life cycle. Being able to map this data back to a single source - the native CAD, QIF enables model-based workflows that are part of the digital manufacturing transformation. The Digital Twin of the CMM will receive measurement data from the actual machine and compare it with the design data. QIF facilitates this data exchange between the real CMM and its Digital Twin.

6.5 Verification and Validation

Digital Twins are complex systems that are sometimes used as virtual testbeds for verification and validation of systems, especially in cases where actual tests are complex to perform. However, the quality of decisions made with Digital Twins depends on the validity of the underlying models. A valid Digital Twin should accurately describe the system that changes over time. Thus, the development of the Digital Twins needs to be validated before its use in supporting decision-making. Verification, Validation, and Uncertainty Quantification (VVUQ) standards need to be followed to ensure that the Digital Twin is built correctly and that the right Digital Twin has been built. Zhang et al. [46] discuss verification and validation methods for Digital Twins, which are categorized into qualitative, quantitative, and integrated methods. Both qualitative and quantitative methods require metrics for Digital Twin validation. These metrics include credibility/fidelity, complexity, standardization, and capability maturity of model construction.

Hua et al. [47] summarized general strategies to validate a Digital Twin. These include visual inspection of the Digital Twin for correctness using established standards, testing properties of the Digital Twin, model-based testing using methods such as input-output conformance testing, and machine learning or artificial intelligence-based testing. Kibira and Weiss [48] used a model-based approach to validate the Digital Twin model of a robot arm. Joint position and orientation data, velocity data, and acceleration data were collected from the physical twin for validation under the model-based approach.

Verification and validation standards include:

- ASME V&V 10: Standard for Verification and Validation in Computational Solid Mechanics [46]
- ASME V&V 20: Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer [50]
- ASME V&V 40: Assessing Credibility of Computational Modeling Through Verification and Validation: Application to Medical Devices [51]
- Other ASME V&V 50, 60, 70, and 80 standards are under development. V&V 50 standards are for advanced manufacturing, and V&V 70 standards are for data-driven models.

7 FUTURE RESEARCH TOPICS FOR STANDARDIZATION

The current four parts of the ISO 23247 series provide a fundamental generic Digital Twin framework for manufacturing. The framework can be extended to industries that employ specialized manufacturing processes and technologies. Future work on this standard may result in new additions supporting the development and validation of Digital Twins. The new research topics for extension of the standard include (1) digital thread for Digital Twins, (2) Digital Twin composition, (3) ontologies of the Digital Twin framework to clarify the entities and relationships, (4) building Digital Twins from reusable components to increase the consistency and reduce the development time, (5) credibility assessment of Digital Twins to increase the trustworthiness and value for decision-making, (6) Digital Twins and the metaverse to provide guidelines that enable the integration between Digital Twins and industrial metaverse, (7) plug and play Digital Twin integration by standardizing interfaces with customers' environment and application platforms, and (8) extending the framework to specific sectors, e.g., semiconductor manufacturing, biomanufacturing, and additive manufacturing to address domain-specific needs [52]. The following subsections discuss the potential new parts of the standard that could enable better and easier Digital Twin development.

7.1 Digital Thread for Digital Twin (ISO 23247-5)

When performing digital transformation, standalone Digital Twins require a lot of duplicated efforts. Therefore, a life cycle approach needs to be taken. However, effectively bringing the life cycle approach is challenging. Guidelines and methodologies for supporting Digital Twin development using a digital thread of the product life cycle will be needed to access all product life cycle information, including design, manufacturing, inspection, and use data, and enable information traceability.

A new part of ISO 23247 on this topic will specify how the digital thread enables the creation, connectivity, management, and maintenance of Digital Twins across the product life cycle. This will involve defining the principles to follow before embarking on a journey for digital transformation, describing methodologies, and providing use case examples. This part will describe how the digital thread supports the generation, implementation, and transformation of Digital Twins in manufacturing. Information in the digital thread enables the Digital Twin to express the changes in a product throughout its life cycle, which can be used to improve future iterations of the product. The digital thread ensures this product life cycle information is readily accessible, traceable, reliable, and secure.

7.2 Digital Twin Composition (ISO 23247-6)

Digital Twin composition implies that multiple Digital Twins are developed and integrated with the support of a digital thread. For example, the Digital Twin of a part and that of the machine that manufactures the part can interact dynamically and seamlessly. When the Digital Twin of a cutting tool, a machine tool, and a part interact, they can be used to determine the tool wear, tolerance conformance, and the machine's health. Digital Twins of multiple partners coordinate and communicate in real time in a supply chain. However, it is challenging to aggregate, compose, and integrate multiple Digital Twins and applications to achieve a new goal. Standard-based methods and guidelines will help achieve this, reduce development time, and mitigate risks for such undertakings.

This part of ISO 23247 will provide guidelines on enabling multiple Digital Twins to communicate and interoperate effectively. The new part could provide generic methodologies, principles, and examples to help users understand the purpose of the Digital Twin and develop the appropriate Digital Twin to address the identified problem(s). Relevant standards and technologies could be selected and applied to demonstrate the integration.

This part of ISO 23247 will also specify Digital Twin composition by defining principles, showing methodologies, and providing use-case examples of Digital Twin configuration, communication, aggregation, composition, integration, and collaboration during manufacturing.

7.3 Ontologies for Digital Twin Framework

The current four parts of the ISO 23247 standard define the terms, relationships, components, and processes necessary for developing a Digital Twin and provide guidelines for Digital Twin implementation. However, logical formalism does not support it, which may lead to inconsistent implementation. The ontologies for the Digital Twin framework will enable the definitions of terms that are both human-understandable and computer-processable, which result in an unambiguous representation of a particular construct and consistent interpretation, regardless of the initial data source. It also enables explicit representation of the connections between different terms; different connections permit a consistent presence and representation of the required metadata. A potential new part of ISO 23247 on this topic could provide an ontology for the Digital Twin framework.

7.4 Building Digital Twins from Reusable Components

Digital Twins could be developed for different control levels depending on the application, including equipment, work cells, production lines, factories, and supply chains. While some approaches exist to support model component reuse [53], most of them are not explicitly designed for Digital Twins. Therefore, almost all Digital Twins are built from scratch, which makes implementations time-consuming and costly. Customized designs also make a Digital Twin challenging to modify, extend, and reuse. Manufacturing knowledge, information attributes, and use case configurations are often developed using different specialized abstractions for each application. The reusability of Digital Twin components in a Digital Twin library could considerably reduce the development cost, time, and the required level of expertise.

A potential new part of ISO 23247 on this topic could provide guidelines on building component libraries and creating templates for organizing data, information, and models. Reusable Digital Twin components may include templates for data collection, common information attributes, and modular models. Digital Twin development would be supported by enabling technologies and relevant standards for various Digital Twin functions. The new part could provide generic methodologies, architectures, frameworks, knowledge bases, and examples for building and using Digital Twin component libraries.

7.5 Credibility Assessment of Digital Twins

The current four parts of ISO 23247 do not cover VVUQ and testing on Digital Twins. Given the potential use of Digital Twins in critical decision-making for various manufacturing applications, the results generated by Digital Twins must be trustworthy for real manufacturing needs. Model credibility assessment, including VVUQ techniques, must be applied throughout the life cycle of Digital Twins. VVUQ should be embedded in the design, creation, and deployment of Digital Twins to establish trust in the model and its outputs [54]. Verification and Validation (V&V) activities are necessary to ensure that a Digital Twin meets its intended purpose and design goals. Uncertainty Quantification (UQ) produces a measure of performance that users can apply as part of a credibility assessment for a given Digital Twin. VVUQ for Digital Twins should be a continual process that adapts to changes in the OME and its digital representation, data inputs, and decisions made [54]. The credibility assessment of Digital Twins may also include factors beyond VVUQ.

Digital Twin testing needs a test system comprising a set of tests for both the OME and its Digital Twin. The test system should also define what an acceptably valid Digital Twin should look like. Grieves proposed a virtual testing method for manufactured products, which can be adapted to Digital Twins [55]. For example, suppose the test system can run a set of tests, and the results of the Digital Twin can't be distinguished from those of the OME within a predefined probability threshold. In that case, the Digital Twin can be regarded as a reasonable representation of the OME. Trust in a Digital Twin also involves trust in the data collected from the OME, the model used in the Digital Twin, the data updating procedure, and the recommended decisions. All these aspects should have a measurable uncertainty, whose existence means that validation (comparison with reality) needs to be treated as a statistical process. Comparison of actual data with model results can be used to estimate the probability that the Digital Twin is a consistent representation of the OME.

Currently, there is no standard process for reporting VVUQ for digital twins. Developing robust VVUQ processes for digital twins remains a challenge. A potential new part of ISO 23247 on this topic could provide guidelines on and methodologies for how to measure uncertainty, how to perform VVUQ and testing for Digital Twins, how to select or construct a credibility assessment framework that supports these activities, and how to assess the credibility of the developed Digital Twins.

7.6 Digital Twins and the Metaverse

The metaverse can support monitoring the manufacturing system in real time, both visually and from a metric standpoint. It could also provide users with an immersive experience. This is now possible because of the maturity of technologies for virtual reality (VR), augmented reality (AR), and extended reality (XR), which can enhance users' visualization experience for manufacturing. For example, it has been demonstrated that AR technologies can be integrated with three-dimensional geometrical product specification and verification standards and practices [56].

A significant feature of the metaverse is the immersive visualization experience along with its human-machine interface. The hardware and software technologies developed for the metaverse can be used by the Digital Twin framework for manufacturing, especially in cases where there is human involvement. For example, the user domain (shown in Figure 2) and user entity of the ISO 23247 standard can use human-machine interfaces provided by the metaverse. Alternatively, a metaverse may be a parallel virtual world that may subsume some of the Digital Twins of a manufacturing enterprise that the metaverse represents. A new part of the ISO 23247 series could include the metaverse concept, its definition, possible scenarios for integrating with manufacturing Digital Twins, including human Digital Twins, guidelines, and methodologies for such integration.

7.7 Extending the Framework to Specific Sectors

Based on the generic framework provided by the initial four parts of the ISO 23247 series, extensions can be developed as new parts of the standard for specific manufacturing sectors such as biomanufacturing, semiconductor manufacturing, and additive manufacturing. The new parts may include specialization of the Digital Twin framework by adding new functional entities or modifying existing functional entities to fit the new requirements. The new parts may also have the use cases implemented for those manufacturing sectors. These use-case implementations may, in turn, help identify new standardization requirements for that manufacturing sector.

The emerging biomanufacturing sector can use the generic framework to develop its Digital Twins, which may constitute a new part of the ISO 23247 series. Similarly, Digital Twins for additive manufacturing may have substantial potential to improve process control, and a new part in the ISO 23247 series can be dedicated to additive manufacturing. In semiconductor manufacturing, an extension of the standard can be developed to address challenges such as obtaining datasets for constructing Digital Twin models and cybersecurity associated with the Digital Twin. Other standards development organizations may adopt the current ISO 23247 series to create Digital Twins for their customer industries.

8 SUMMARY

Digital Twins are becoming more prevalent in a wide variety of industries, including manufacturing. However, a standards-based ecosystem of Digital Twins has not yet been established. Developing and integrating Digital Twins presents significant challenges. Foundational work is needed to support an open marketplace for Digital Twin developers, users, and technology and service providers. This includes the development of standardized frameworks, reference models, interface specifications, and VVUQ methodologies to provide a solid foundation for ensuring the interoperability, validity, security, and trust of Digital Twins. This Chapter focuses on applying Digital Twins in manufacturing within a framework of standards, identifies current challenges, reviews relevant standardization efforts, and introduces the ISO

Digital Twin framework standard for manufacturing, ISO 23247. This work also presents use case scenarios and discusses some potential research directions and future standardized topics. A use case is presented to illustrate the Digital Twin development process by applying relevant standards. The example is obtained from the Digital Twin development efforts for a robot work cell in a Digital Twin Lab at NIST.

Future efforts include performing measurement science research to support the development and integration of digital twins in manufacturing, working with Industrial consortia and standards development organizations to prioritize the standardization topics (e.g., interoperability and VVUQ), formulating working groups and project teams to develop the new parts of the Digital Twin standards, and enhancing the Digital Twin Lab to serve as a digital twin testbed to support digital twin prototyping and standards development and testing.

DISCLAIMER

Certain commercial products and systems are identified in this chapter to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose. No approval or endorsement of any commercial product by NIST is intended or implied.

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